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# Efficiencies and pollutant emissions from forced-draft biomass-pellet semi-gasifier stoves: Comparison of International and Chinese water boiling test protocols

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## ABSTRACT

Biomass fuels are widely combusted in rural China, producing numerous air pollutants with great adverse impacts on human health. Some improved cookstoves and pellet fuels have been promoted. To evaluate the performance of pellet-gasifier stoves, efficiencies and pollutant emissions were measured following International and Chinese water boiling tests (WBTs). Compared with traditional stoves and unprocessed biomass fuels, increased efficiencies and lower emissions of pollutants including carbon monoxide (CO), particulate matter (PM), parent and derivative polycyclic aromatic hydrocarbons (PAHs) were revealed for pellet-gasifier stoves. However, the calculated emission rates (ERs) of CO and $PM_{2.5}$ cannot meet the ER targets recently suggested by WHO indoor air quality guidelines (IAQGs). Better control of air mixing ratio and gross flow rates of primary and secondary air supply greatly reduced emissions and increased efficiencies. Differences among testing protocols are the key factors affecting the evaluation of stove performance. With longer burning duration and higher power, the Chinese WBT had statistically higher efficiencies, gas temperature, and lower pollutant emissions ($p < 0.10$) compared to those obtained through the International WBT. Statistically significant differences between the two protocols indicate the need for further efforts in emission tests and methodology development before the release of a well-accepted international testing protocol.

## Introduction

Globally, over 2.6 billion people are still relying on traditional biomass fuels for household cooking activities (International Energy Agency, IEA, 2013). Incomplete burning of traditional fuels usually produces large amounts of air pollutants, including CO, PM, black carbon (BC), and organics like PAHs, and subsequently leads to severe household air pollution, adverse impacts on human health, and local and regional climate change (Reid et al., 2012; Smith, 2013a; WHO, 2009; Rao et al., 2013). Residential fuel combustion is one major source of many incomplete combustion products, especially in developing countries. Household air pollution has been recognized as one of the top environmental risk factors affecting human health globally and results in approximately four million premature deaths annually (Lim et al., 2013; Zhang and Smith, 2007; Smith et al., 2013b, 2014).

Traditional stoves were often lower in heating transfer efficiency (HTE) and thermal efficiency, had a long time duration for cooking, consumed a large amount of fuels, and produced high pollutant emissions. Consequently, notable adverse impacts on air quality and human health are yielded (Edwards et al., 2004; Jetter et al., 2012; Clark et al., 2013; Shen et al., 2015a). Efforts have been made to increase HTE and/or thermal efficiency in the stoves' performance, so as to reduce fuel consumption and lower air pollution (Smith et al., 2000; Jetter et al., 2012; Dutt and Ravindranath, 1993; Shen et al., 2015b; Kshirsagar and Kalamkar, 2014). The experience in China showed that the development of stoves experienced four stages (Shen et al., 2015b). Improved stoves were promoted and benefited air quality and human health from the 1980s (some simple improved stoves with

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*Abbreviations:* BC, black carbon; CCT, controlled cooking test; CO, carbon monoxide; EC, elemental carbon; EF, emission factor; ER, emission rate; GFF, glass fiber filter; HTE, heat transfer efficiency; IAQ, indoor air quality; IAQG, indoor air quality guideline; KPT, kitchen performance test; LHV, lower heating value; MCBM, Monte Carlo box model; MCE, modified combustion efficiency; MDL, method detection limit; OC, organic carbon; OTE, overall thermal efficiency; PAH, polycyclic aromatic hydrocarbon; PM, particulate matter; PUF, polyurethane foam plug; QFF, quartz fiber filter; VM, volatile matter; WBT, water boiling test.

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ventilation, grates, and chimney) when the National Improved Stove Program was initiated (Shen et al., 2015b; Smith et al., 1993a). Currently, after the fast research and development of stoves in China, some high-efficiency clean stoves like gasifier stoves with primary and secondary air supply, and forced-draft stoves are available, which are expected to be able to lower pollutant emissions and improve air quality after an effective intervention program.

Evaluating efficiency and emission performance is a good way to compare one fuel–stove combination with another (Jetter et al., 2012). In addition to fuel and stove properties, the burn cycle protocols and other factors like sampling and laboratory analysis can affect the results of emission and efficiency greatly. According to existing standards and guidelines, laboratory-simulated emission measurements can repeat the burning processes, and thus have been widely used in the evaluation and comparison of performance among different fuel–stove combinations. Though the WBT is commonly utilized in laboratory emission measurement, the detailed procedure varies greatly in various protocols (Makonese et al., 2011; Arora et al., 2014). For example, the International WBT is somewhat different from the one (the Chinese WBT) commonly used in China in time control, water temperature, and parameter calculation and description (Water Boiling Test, WBT Version 4.1.2, 2009; Chinese Water Boiling Test, WBT, 2008), as we present in the following method section.

In this study, three gasifier stoves burning pellets were tested for efficiencies, emission factors (EFs) and ERs of CO, PM, elemental carbon (EC), organic carbon (OC), and PAHs in a laboratory using both International and Chinese WBTs methods. The differences among three pellet-gasifier stoves and between the two WBTs are compared and discussed. It is expected that the results will provide important data relevant to clean stove intervention programs and contribute to the development of an international standard test protocol in the future.

## Experimental

### Fuels and stoves

Three different models of pellet-gasifier stoves sold in some rural areas of China were tested in this study. All of them have primary and secondary air supply devices controlled through a fan. By turning the dials on front of the stoves, the flow rate of primary and secondary air can be adjusted. It is noted that some intervention programs are promoted in rural China, and the stoves in the present study are under strong consideration in these intervention programs (Carter et al., 2014). The photos and detailed manufacturing information are shown in Table **1** and Fig. **1**. Stove 1 was purchased from the local market in Shanxi, Northern China, and primary and secondary air supply can be controlled separately. Stove 2 was from Hunan in Southern China. With only one dial in front, it can control the gross air supply fan power; however, the ratio between primary and secondary air is preset by the manufacturer and cannot be altered separately by the user. Stove 3 was from Henan in central China and it adjusts the burning conditions by varying the ratio of primary and secondary air supply under a stable gross air supply. The same batch of pellets made with cornstalk with a small amount of cow dung (~9:1), was used in each stove. A small amount of dry high-resin pinewood (approximately 100 g) was used for initial lighting. The measured carbon content, nitrogen content, hydrogen content, oxygen content (by difference), volatile matter (VM), moisture (wet basis), and lower heating value (LHV) of the pellet were 42%, 1.44%, 6.55%, 55.23%, 65.34%, 14%, and 17.0 MJ/kg, respectively. The ash content was around 9.4%.

**Table 1**
Information on the three Chinese pellet-gasifier stoves tested in this study

| Stove number | Stove model | Production year | Manufacturer | Location |
|---|---|---|---|---|
| Stove 1 | CKQ-80 | 2009 | Jinqilin | Shanxi, China |
| Stove 2 | CLKB 2.5-IY | 2010 | Xunda | Hunan, China |
| Stove 3 | HLJF-CS 3.5 | 2011 | Heluo | Henan, China |

### Water boiling tests

The International and Chinese WBT protocols are different in the operation procedure and calculation. Three test phases including cold start, hot start, and simmer phases are tested in the International WBT protocol. The cold start phase starts from the fuel lighting by heating a pot of water (5 L) from the ambient temperature to the boiling point. When the cold start phase is completed, the remaining fuels are weighed. The hot start phase follows with the stove at the same operating procedure and heating another pot of water from ambient to boiling temperature. The simmering phase maintains a measured amount of water at just below the boiling point for 45 min (Water Boiling Test, WBT Version 4.1.2, 2009). In the present test, the simmering phase was not tested as it is seldom used in real practice in China. The pot is not covered during the whole test. As previous studies found that the differences in pollutant emissions between the cold start and hot start of the International WBT was small for stoves with relatively small thermal mass, an averaged value was calculated representing a value for high power performance, as specified by the International Standard Workshop Agreement. tiered stove rating framework (Carter et al., 2014; Water Boiling Test, WBT Version 4.1.2, 2009; International Workshop Agreement, IWA, 2012).

In the Chinese WBT protocol, there is only one test phase (Chinese Water Boiling Test, WBT, 2008). Once fuel is ignited, the pot with 5 L of water and lid is put onto the stove, and the test starts. When the water temperature reaches the boiling point, the pot cover is removed. But remaining fuels are left in the stove chamber and burned. The test ends when the water temperature decreases to 5 °C below the boiling point. The schematic diagram showing the water temperature over time for these two WBTs is provided in Fig. **2**.

### Calculation

In both Chinese and International WBT protocols, water mass is preweighed, and the mass of water evaporated is measured. Water temperature is measured continuously throughout the test. The initial water temperature, water boiling temperature, and test duration are recorded. These parameters are used to calculate the performance indicators, including thermal efficiency and pollutant EFs.

Overall thermal efficiency (OTE) is a measure of the ratio of useful energy delivered (to the water in the pot) to the fuel energy from complete combustion. The useful energy delivered includes the energy for both water heating and water evaporation. The calculation of OTE in both International and Chinese WBT protocols is the same, using the following equation:

$$OTE = \frac{\Delta \boldsymbol{E}_{H_2\boldsymbol{O},Heat} + \Delta \boldsymbol{E}_{H_2\boldsymbol{O},evap}}{E_{\text{released},c}}$$

$\Delta \boldsymbol{E}_{H_2O,heat}$: Calorific heat transferred to water in the pot which was heated from room temperature to boiling point.

$\Delta \boldsymbol{E}_{H_2O,evap}$: Calorific heat transferred to the water in the pot to evaporate.

$\boldsymbol{E}_{released,c}$: Calorific heat delivered by the equivalent dry fuel consumed.

The modified combustion efficiency (MCE), defined as $CO_2/(CO + CO_2)$ (molar basis), is a reasonable proxy for efficiency and also the percentage of the chemical energy in the fuel that is actually released. It indicates how well fuel is burned. HTE is the ratio of energy delivered to the pot versus the total heat energy released from the fuel burning. However, in most circumstances, it is hard to determine HTE. It was